Discovery of photospheric Ca X emission lines in the far-UV spectrum of the hottest known white dwarf (KPD 0005+5106)[*]

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ABSTRACT

For the first time, we have identified photospheric emission lines in the far-UV spectrum of a white dwarf. They were discovered in the *Far Ultraviolet Spectroscopic Explorer* spectrum of the hot ($T_{eff} \approx 200\,000$ K) DO white dwarf KPD 0005+5106 and they stem from extremely highly ionized calcium (Ca X $\lambda\lambda$ 1137, 1159 Å). Their photospheric origin is confirmed by non-LTE line-formation calculations. This is the highest ionisation stage of any element ever observed in a stellar photosphere. Calcium has never been detected before in any hot white dwarf or central star of planetary nebula. The calcium abundance determination for KPD 0005+5106 (1-10 times solar) is difficult, because the line strengths are rather sensitive to current uncertainties in the knowledge of effective temperature and surface gravity. We discuss the possibility that the calcium abundance is much lower than expected from diffusion/levitation equilibrium theory. The same emission lines are exhibited by the [WCE]-type central star NGC 2371. Another Ca X line pair ($\lambda\lambda$ 1461, 1504 Å) is probably present in a *Hubble Space Telescope* spectrum of the PG1159-type central star NGC 246.

Key words. Stars: abundances – Stars: atmospheres – Stars: evolution – Stars: AGB and post-AGB – White dwarfs

1. Introduction

Observations of hot (pre-) white dwarfs with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) have revealed a large number of chemical elements that were never detected before in these objects. Their abundances can be used either to probe interior processes in previous stellar evolution phases or to test predictions from theories for element diffusion and radiative levitation.

We have recently identified Ne VIII lines in the hottest ($T_{eff} \gtrsim 150\,000$ K) non-DA (pre-) white dwarfs, i.e. objects of spectral type PG1159, DO, and [WCE] (Werner et al. 2007). The discovery of these lines in the hottest known DO white dwarf KPD 0005+5106 was particularly surprising, because this proves that its effective temperature must be much higher than previously thought (200 000 K instead of 120 000 K).

KPD 0005+5106 was frequently observed by *FUSE* as a calibration target over its entire lifetime. We have co-added all available spectra and obtained datasets with very high S/N ratio. A careful inspection of spectra taken with different detectors revealed the presence of two hitherto unidentified *emission* lines. While there is still a large number of unidentified absorption lines present in *FUSE* spectra of hot white dwarfs (WDs), the discovery of emission features is unique and was completely unexpected. In this *Letter* we identify them as Ca X lines and present results of non-LTE modeling in order to confirm their photospheric origin and to perform an abundance determination.

We present observations and line identifications in Sect. 2 and describe the modeling in Sect. 3. The results from line-profile fits are presented in Sect. 4. We conclude with Sect. 5.

## 2. Observations and Ca X line identifications

The *FUSE* instrument consists of four independent co-aligned telescopes and spectrographs; two with Al+LiF optical coatings and two with SiC coatings. Taken together, the four channels span the wavelength range 904–1187 Å with a typical resolving power of $R \approx 20\,000$. Further information on the *FUSE* mission and instrument can be found in Moos et al. (2000) and Sahnow et al. (2000). KPD 0005+5106 was observed as a wavelength calibration object throughout the *FUSE* mission (observations M1070201–M1070234), in each of the spectrograph apertures (LWRS, MDRS, HIRS), and once under program P1040101 in LWRS. All observations were obtained in TTAG mode, except for three early HIST mode observations; the latter were excluded as they have different residual distortions in the wavelength scale. All exposures were processed with the final version, v 3.2.2, of CalFUSE (Dixon et al. 2007). Spectra for each channel were shifted to place absorption lines from low-ionization interstellar gas at a heliocentric velocity of -15 km s^{-1} (Werner et al. 1996), and combined. Variations in losses due to event bursts and channel misalignments caused the net exposure times to vary: HIRS times varied from 7.0 ks in SiC2a to 17.9 ks in LiF2b; MDRS times varied from 11.6 ks in SiC1a to 18.6 ks in LiF2b; LWRS times varied from 28.5 ks in LiF1b to 33.6 ks in LiF2b. The net signal ranges from 700 counts per 0.013 Å pixel in the HIRS spectra to 1200 c/pix in MDRS and as much as 2700 c/pix in LWRS. The Ca X emission features are seen clearly in each of the six available spectra (LiF1b and LiF2a in each of HIRS, MDRS, LWRS). These six spectra were then resampled onto a common wavelength scale and combined to produce a single spectrum with an effective exposure time of 122.2 ks.

The UV spectrum of NGC 246, taken with the *Space Telescope Imaging Spectrograph* (*STIS*) with grating E140H
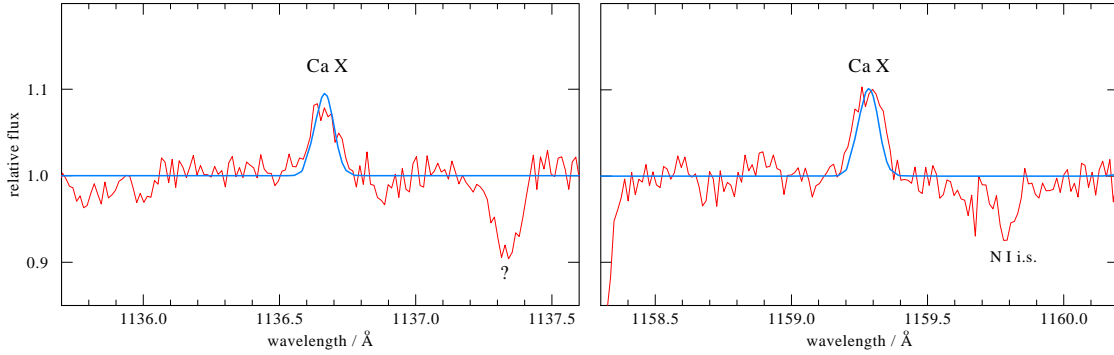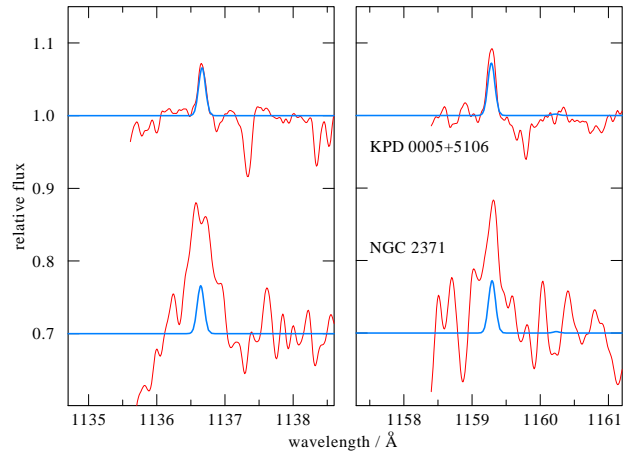
Fig. 1. The two Ca X emission lines discovered in KPD 0005+5106 (thin graphs). Overplotted is the spectrum from a model with $T_{\mathrm{eff}} = 200\,000$ K, $\log g = 6.2$, and solar Ca abundance. The model was convolved with a Gaussian with FWHM=0.05 Å in order to match the instrumental resolution.
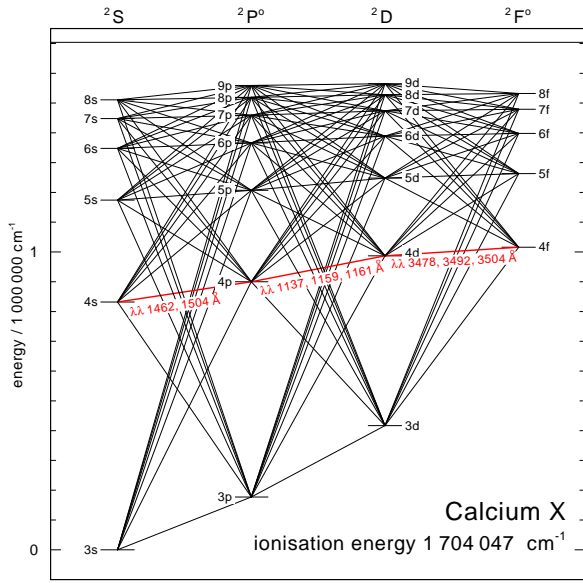
Fig. 2. Grotrian diagram of our Ca x model ion. Lines discussed in the text are caused by transitions between $n = 4$ sublevels. The 4p–4d transition causes the observed UV emission lines.

Fig. 3. The two Ca x emission lines discovered in KPD 0005+5106 (top spectra) are also seen in the [WCE] central star NGC 2371. The model profiles are the same as in Fig. 1. No attempt is made to fit the possibly wind-contaminated [WCE] profiles. For clarity, the *FUSE* spectra were smoothed with Gaussians (FWHM 0.05 and 0.1 Å, respectively). The model spectra (thick lines) were convolved with 0.1 Å Gaussians.

aboard the *Hubble Space Telescope* (*HST*) was retrieved from the MAST archive.

In the *FUSE* spectrum of KPD 0005+5106 we detected two emission lines, located at photospheric rest wavelengths $\lambda\lambda$ 1136.5, 1159.2 Å (Fig. 1; radial velocity +35 km s^{-1}; Werner et al. 1996). We identify these lines as due the 4p ^{2}S $-$ 4d ^{2}P$^{\mathrm{o}}$ transition in the Ca X ion (Fig. 2). Compared to the Ritz wavelengths in the NIST[1] database, both observed lines are located at wavelengths shorter by 0.3 Å. Their NIST gf-values are $\log g_i f_{ik} = 0.23$ and 0.46, respectively. The third line component of this transition is located at λ 1161.4 Å according to NIST, so that in reality we expect it to be found at λ 1161.1 Å. Its gf-value, however, is much smaller ($\log g_i f_{ik} = -0.47$) explaining the fact that we cannot detect it in the observation. (This is confirmed by our line-formation calculations.)

We searched for the two Ca X lines in other hot DO white dwarfs and PG1159 stars, but to no avail. As we will demonstrate below (Sect. 4), this is a consequence of the extremely high T_{eff} of KPD 0005+5106 combined with a relatively low surface gravity. However, these lines are seen in the very hot, early-type Wolf-Rayet central star NGC 2371 (Fig. 3). For this object we did not attempt to fit these lines with our (static) model atmospheres, because the profiles might be affected by the stellar wind.

In the course of our model calculations we found that further Ca X lines might be detectable in other wavelength regions. The 4s–4p transition gives rise to a line doublet at $\lambda\lambda$ 1461.8, 1503.8 Å. Our models predict only marginal emission features for KPD 0005+5106, which cannot be detected in archival spectra taken with the *Faint Object Spectrograph* aboard *HST* and high-resolution spectra from the *International Ultraviolet Explorer*. However, for NGC 246 our models predict absorption lines that are possibly present in a *HST/STIS* spectrum (Fig. 4). The positions of the tentatively identified absorption features in NGC 246 differ from the NIST wavelengths by -0.7 and -0.2 Å, respectively.

[1] http://physics.nist.gov/ PhysRefData/ASD/index.html
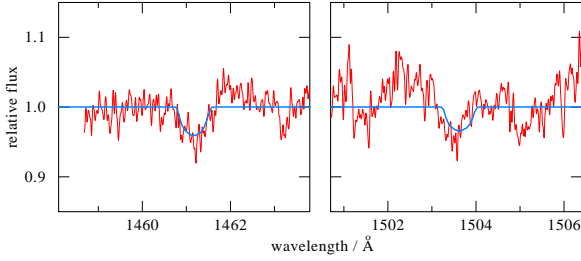
Fig. 4. *HST/STIS* spectrum of the PG1159-type central star NGC 246 and computed profiles for the 4s–4p doublet of Ca X. Their shape reflects the stellar rotation of $v \sin i = 70 \, \mathrm{km \, s^{-1}}$. The observation was smoothed with a Gaussian with FWHM=0.03 Å.

Fig. 5. Ionization fraction of calcium as a function of atmospheric depth in the model with $T_{\mathrm{eff}} = 200\,000$ K, log $g = 6.2$, and solar Ca abundance.

From NIST level energies one expects the two strongest lines of yet another transition of Ca X (4d–4f) to be located in the optical UV at $\lambda\lambda$ 3478, 3492 Å, respectively. A high-resolution spectrum of NGC 246 taken with ESO's *Very Large Telescope* and the UVES spectrograph as part of the SPY survey (Napiwotzki et al. 2003) reveals no line features there. Our model for NGC 246 predicts absorption lines with a depth of only 5% relative to the continuum. The relatively fast rotation ($v \sin i = 70 \, \mathrm{km \, s^{-1}}$) smears the line features considerably, and they remain hidden in the noise. Similar weak absorption profiles for these lines are predicted for KPD 0005+5106, but no appropriate observations are available.

3. Model atmospheres and calcium line-formation

We have designed a calcium model atom for NLTE line-formation calculations. These were performed using and keeping fixed the physical structure (temperature, densities) of line-blanketed NLTE model atmospheres which are described in detail in Werner et al. (2004). In short, they are plane-parallel and in hydrostatic and radiative equilibrium. The models are composed of He, C, O, and Ne. For KPD 0005+5106, we assumed helium-dominated atmospheres with admixtures of C=0.003, O=0.0006, Ne=0.01 (mass fractions). The high neon abundance was derived from Ne VIII lines (Werner et al. 2007). The C and O abundances are uncertain, because they were derived in earlier work that assumed that KPD 0005+5106 is relatively cool ($T_{\mathrm{eff}} = 120\,000$ K; Werner et al. 1996). We verified that varying the C and O abundances within reasonable limits does not change the Ca X lines significantly. A series of models with various T_{eff} and log g values was computed to study the dependency of the Ca X lines on these parameters (see Sect. 4). For NGC 246 we adopted $T_{\mathrm{eff}} = 150\,000$ K, log $g = 5.7$, and the composition He/C/O/Ne=0.62/0.30/0.06/0.02 (Werner et al. 2007).

The Ca model atom considers the ionization stages VIII–XII, represented by 1, 15, 25, 4, 1 NLTE levels, respectively, plus a number of LTE levels. In the ions Ca IX−XI we include 23, 126, and 2 line transitions, respectively. Atomic data were taken from the NIST, Opacity (Seaton et al. 1994), and IRON (Hummer et al. 1993) Projects databases (TIPTOPbase[2]). Fine-structure splitting is accounted for in the final formal solution for the synthetic line-profile computation, distributing the level populations among sublevels assuming LTE. For all lines we assumed quadratic Stark broadening for the profile calculation.
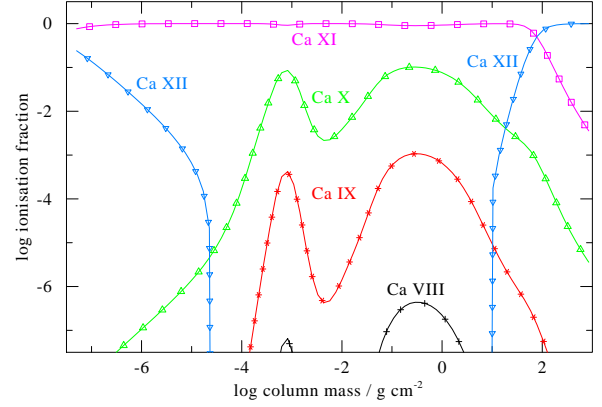
Particularly for the Ca X $\lambda\lambda$ 1137, 1159 Å lines the values of the oscillator strengths differ between the OP and NIST databases. We use the OP values for our NLTE level population iterations, because they are complete, in contrast to the NIST database. For the final line-profile calculation we prefer the NIST values, which are higher than the OP values by $\approx 25\%$. The differences do not affect our conclusions.

Photoionization cross-sections are taken from the Opacity Project database when available or, otherwise, computed in a hydrogen-like approximation. Electron collisional rates were calculated with the usual approximation formulae. The Ca model atoms that were used for this analysis have been developed in the framework of the *German Astrophysical Virtual Observatory* (*GAVO*[3]) project and are provided within the Tübingen Model-Atom Database *TMAD*[4].

4. Results

Figure 1 shows a fit to the Ca X emission lines in KPD 0005+5106 with a model $T_{\mathrm{eff}} = 200\,000$ K, log $g = 6.2$, and a solar Ca abundance (log Ca $= -4.22$, mass fraction; Asplund et al. 2005). In Fig. 5 we show the ionization structure of Ca throughout this model atmosphere. Within the entire line-forming region Ca XI is dominant, followed by Ca X. In order to achieve the observed emission strength in a model with this temperature and Ca abundance, the surface gravity must be that low (log $g = 6.2$). This is 0.3 dex lower than what is preferred from the He II line spectrum (Werner et al. 2007). We will show, however, that the fit to the Ca X lines can be achieved with more than one parameter set.

The occurrence of this line emission can be understood when the non-LTE departure coefficients $b_i = n_i^{\mathrm{NLTE}}/n_i^{\mathrm{LTE}}$ for the populations n_i of the involved atomic levels and the line source function S_l are inspected (Fig. 6). The line source function is determined by the ratio of the departure coefficients of the lower and upper levels (i, j) and can be written as $S_l/B_\nu = [\exp(h\nu_{ij}/kT) - 1]/[(b_i/b_j) \exp(h\nu_{ij}/kT) - 1])$, where B_ν is the Planck function. An overpopulation of the upper level relative to the lower (i.e. $S_l/B_\nu > 1$) may lead to line emission. In fact, this condition is fulfilled in the line-forming region (Fig. 6), although both levels are underpopulated (i.e. $b_i < 1$).
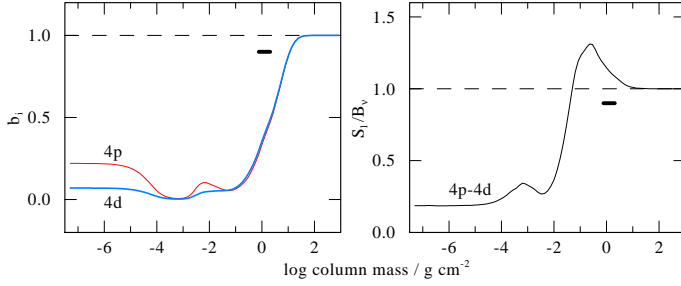
Fig. 6. *Left:* Departure coefficients b_i for the 4p and 4d levels that cause the Ca X emission lines. *Right:* Ratio of 4p–4d line source function S_l to Planck function B_ν at line centre. The thick horizontal lines near $\log m = 0$ denote the line formation region. Dashed lines correspond to the LTE case ($b_i = 1$ and $S_l/B_\nu = 1$). Model parameters as in Fig. 5.

Fig. 7. Profile shapes of the Ca X $\lambda\lambda$ 1137, 1159 Å lines as a function of T_{eff}, $\log g$, and Ca abundance, as given by the labels.

We have computed a small grid of models with different T_{eff} and $\log g$ (representing the uncertainties with which these parameters are known) and Ca abundances. The results are presented in Fig. 7. Generally, high T_{eff} and low $\log g$ is necessary in order to bring this line into emission (left and right upper panels). If T_{eff} decreases (and/or $\log g$ increases), the lines first turn from emission into weak absorption features and then disappear at about 140 000 K. This explains why other DOs do not exhibit these lines: they are significantly cooler and have higher gravities compared to KPD 0005+5106.

The sensitivity of these emission lines to the calcium abundance is complicated and depends on T_{eff} and $\log g$ of the atmosphere (Fig. 7, left and right lower panels). Increasing the Ca abundance over the solar value can strongly increase the emission height (model $T_{\text{eff}} = 200\,000$ K $\log g = 6$) or decrease it (model $T_{\text{eff}} = 200\,000$ K $\log g = 6.5$). For KPD 0005+5106 we achieved a good fit at $T_{\text{eff}} = 200\,000$ K, $\log g = 6.2$, and solar Ca abundance. As mentioned, however, our previous analysis favors a gravity higher by 0.3 dex. Increasing the gravity to $\log g = 6.5$ makes the emission weaker, but this can be compensated by simultaneously increasing the Ca abundance to 3 times the solar value and T_{eff} to 220 000 K. A much higher abundance, as predicted by diffusion theory, can be excluded. We have calculated models with 70 times solar Ca abundance. The emission line peak heights hardly change in the $T_{\text{eff}} = 200\,000$ K, $\log g = 6.2$ model when Ca is increased from solar to 70 times solar; however, detailed inspection of the relative strength of both lines shows that it is not in agreement with the observation. In the observation as well as in the $\approx$ solar Ca abundance models the 1159 Å emission is stronger than the 1137 Å emission, as can be expected from the gf-value ratio. In the 70 times solar models the emission strength ratio is reversed, in contrast to the observation.

Concerning PG1159 stars, the behaviour of these Ca lines is rather similar and therefore not shown in detail here. There are seven objects that are hot enough and for which *FUSE* spectroscopy is available. These are the low-gravity central stars of planetary nebulae K1-16, Longmore 4, RX J2117.1+3412, NGC 246 ($T_{\text{eff}} = 140\,000$–170 000 K, $\log g \approx 5.5$–6), the higher-gravity objects PG1520+525 and PG1144+005 ($T_{\text{eff}} = 150\,000$ K, $\log g = 6.5$–7), as well as the peculiar H1504+65 ($T_{\text{eff}} = 200\,000$ K, $\log g = 8$). Model calculations were performed for all of these objects with solar Ca abundance (diffusion is not at work in these objects' atmospheres; see Unglaub & Bues 2000). They exhibit the
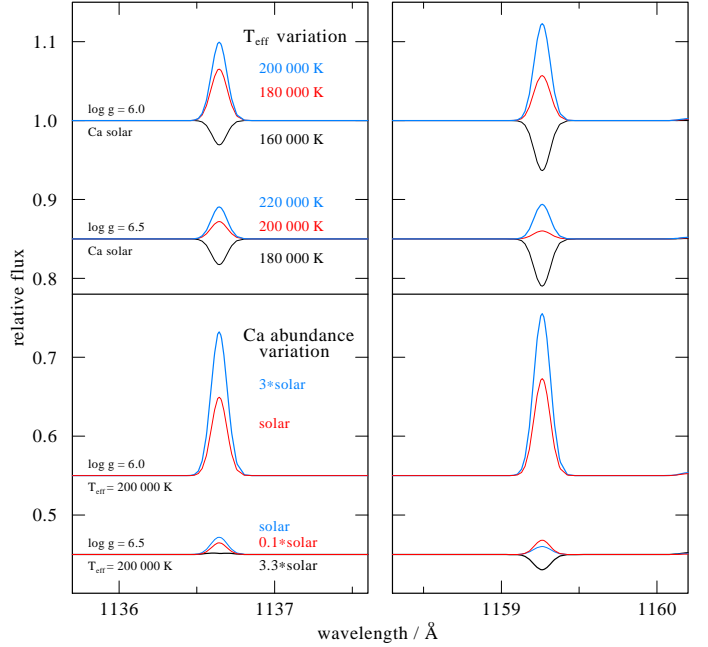
Ca x $\lambda\lambda$ 1137, 1159 Å lines as weak absorption features with a maximum depth of 5% of the continuum flux. Such weak lines cannot be detected in the available *FUSE* spectra.

5. Summary and conclusions

We have discovered Ca X emission lines in far-UV spectra of the DO white dwarf KPD 0005+5106. This is the first detection of photospheric emission lines in this spectral range of any hot (pre-) white dwarf. Provencal et al. (2005) discovered low-ionisation emission lines in *HST/STIS* UV spectra of two relatively cool ($T_{\text{eff}} \approx 12\,500$ K) He-rich white dwarfs (spectral type DQ). It was shown, however, that they are chromospheric in origin. The Ca X lines are the highest ionisation stage of any element identified in any stellar photosphere. Our discovery also represents the first identification of calcium in hot (pre-) WDs.

The Ca abundance in KPD 0005+5106 is in the range $\approx$1–10 times solar. A more precise determination from the emission lines is not possible. A comparison of this result with predictions from radiative levitation/gravitational diffusion equilibrium theory is difficult because T_{eff} and $\log g$ of KPD 0005+5106 are outside of the range considered by Chayer et al. (1995; their Fig. 20). For the closest parameters ($T_{\text{eff}} = 130\,000$ K, $\log g = 7$) a huge overabundance is predicted (2500 times solar). Our estimate for $\log g$ is smaller (6.2–6.5) which would result in an even higher overabundance. On the other hand it is impossible to make a solid estimate for the effect of the higher T_{eff} (200 000–220 000 K) on the behaviour of the Ca equilibrium abundance, because the dominant ionisation stage in KPD 0005+5106 is Ca xi, while it is Ca viii in the hottest Chayer et al. model ($T_{\text{eff}} = 130\,000$ K, $\log g = 7.5$). Looking at the behaviour of other elements (S, Ar), namely how their equilibrium abundance changes when their (respective isoelectronic) ionisation stages increase (with increasing T_{eff}), it is suggestive that the Ca abundance at $T_{\text{eff}} = 200\,000$ K is lower than at 130 000 K, but not by orders of magnitude. Although detailed calculations are required

for a definitive statement, we conclude that the atmosphere of KPD 0005+5106 is probably not in levitation/diffusion equilibrium. This is confirmed by the diffusion/mass-loss calculations of Unglaub & Bues (2000) which suggest that KPD 0005+5106 has yet to cross the wind-limit on its evolutionary track, meaning that mass-loss is large enough to prevent both gravitational settling and the accumulation of radiatively supported heavy elements. In this case, KPD 0005+5106 is not a descendant of the PG1159 stars. An evolutionary link to the He-dominated central stars of spectral type O(He) and to the RCrB stars has been suggested (Werner et al. 2008).

If unaffected by diffusion processes, then the photospheric composition of KPD 0005+5106 is the consequence of previous evolutionary phases. In contrast, the presence of Ca in the atmospheres of cooler white dwarfs (spectral types DAZ and DBZ, with low-ionisation optical Ca absorption lines) requires on-going accretion of circumstellar matter, because gravitational settling rapidly removes heavy elements from the photosphere (e.g. Koester & Wilken 2006).

The non-detection of the Ca x $\lambda\lambda$ 1137, 1159 Å lines in the hottest PG1159 stars is explained by undetectably weak absorption line features in the models. Another Ca x line pair ($\lambda\lambda$ 1462, 1504 Å) is possibly present in absorption in NGC 246 and suggests a roughly solar Ca abundance. The only other object in which we discovered the Ca x $\lambda\lambda$ 1137, 1159 Å emission lines is the [WCE]-type central star NGC 2371. This corroborates the extraordinarily high effective temperature of this object.

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